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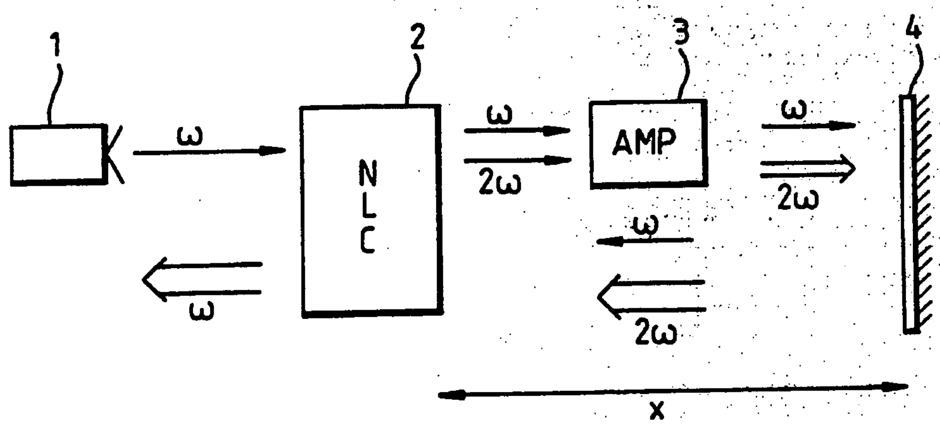

(57) Abstract

A nonlinear optical device comprises a nonlinear component such as a frequency doubling crystal (2) adapted to transmit pulses of electromagnetic radiation at a predetermined fundamental frequency and to generate one or more harmonic frequency signals therefrom. The device also includes a spectral filter device such as a dichroic mirror (4) capable of differentially attenuating optical signals at the fundamental frequency to a greater extent than those at a selected harmonic frequency. An amplifier (3) is tuned to amplify the optical signals at the selected harmonic frequency, and the amplified signals at the selected harmonic frequency are recombined together with transmitted optical signals at the fundamental frequency such that the optical signals at the selected harmonic frequency are at least partially reconverted into the fundamental frequency.

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NONLINEAR OPTICAL DEVICE

This invention relates to nonlinear optical devices, i.e. those including a nonlinear optical component such as a nonlinear crystal capable of generating harmonic frequency components from an optical signal input thereto.

In Appl. Phys. B.45 191-195 K.A. Stankov describes an arrangement in which a nonlinear crystal is used for second harmonic generation, the SHG signal being reflected by a dichroic mirror. A phase adjusting glass plate regulates the phases of the optical signals at the fundamental and second harmonic frequencies such that partial reconversion into the fundamental takes place during the second passage through the nonlinear crystal. The arrangement is described as being used to mode lock a Nd:YAG laser.

The present invention seeks to provide an improvement to the above described type of arrangement.

Accordingly, there is provided a nonlinear optical device comprising a source of intense pulses of electromagnetic radiation at a predetermined fundamental frequency; a nonlinear optical component adapted to transmit the pulses of electromagnetic radiation and to generate one or more harmonic frequency signals therefrom; an amplifier tuned to amplify optical signals at a selected harmonic frequency; and a recombination device adapted to recombine the amplified signals at the selected harmonic frequency together with the transmitted optical signals at the fundamental frequency such that the optical signals at the selected harmon frequency are at least partially reconverted into the fundamental frequency.

Such a nonlinear optical device is capable of operating as an optical amplifier of optical signals at a predetermined fundamental frequency and, as the actual amplification takes place at a select harmonic frequency, the amplified spontaneous emission (ASE) at the fundamental frequency is minimised.

According to a preferred arrangement there is additionally provided a spectral filter device capable of differentially attenuating optical signals at the fundamental frequency to a greater extent than those at the selected harmonic frequency. As the conversion of the fundamental to the selected harmonic frequency is intensity dependent, the combination of the nonlinear component and the spectral filter enhances the contrast ratio between the peak intensity of a main pulse and the intensity of any low lying pre-pulse or pedestal. By amplifying the optical signals at the selected harmonic frequency prior to their recombination with the fundamental, there results in a significant further improvement to the contrast ratio, and hence the quality of the pulses.

Provided the amplification at the selected harmonic frequency is sufficient to overcome the attenuation caused by the spectral filter, the above described arrangement will continue to act as an amplifier of optical pulses at the fundamental frequency. Furthermore the pulses will be compressed by their passage through the optical device, and amplification at the selected harmonic frequency will also enhance this pulse compression. The device is therefore capable of providing amplified, compressed pulses having an enhanced contrast ratio and hence less amplification of any unwanted pre-pulses or pedestals. Preferably the nonlinear optical component is adapted to generate a second harmonic frequency optical signal as the selected

harmonic frequency, although higher harmonic signals can be employed if desired.

Conveniently, the nonlinear optical component additionally constitutes the recombination device. By constraining the amplified optical signals to pass through the nonlinear optical component a second time with the appropriate relative phase, the nonlinear component can be employed both as a harmonic generator and a recombination device.

The nonlinear optical component is conveniently a frequency doubling crystal such as a B Barium Borate crystal. Preferably the spectral filter device, where one is provided, comprises a dichroic mirror. A dichroic mirror with a high reflectivity at the selected harmonic frequency and a low reflectivity at the fundamental frequency is capable of providing the enhancement to the contrast ratio discussed above, and also redirecting the optical signals to pass again through the nonlinear optical component where such is to be employed to recombine the fundamental and harmonic signals. Where a spectral filter device such as a dichroic mirror is provided, the amplification of the selected harmonic frequency can take place before filtering, after filtering, or even both before and after filtering providing that the amplifier gain has not been saturated.

The invention further resides in a nonlinear optical device comprising a nonlinear optical component adapted to transmit pulses of electromagnetic radiation at a predetermined fundamental frequency and to generate one or more harmonic frequency signals therefrom; a spectral filter device capable of differentially attenuating optical signals at the fundamental frequency to a greater extent than those at a selected harmonic

frequency; an amplifier tuned to amplify optical signals at the selected harmonic frequency; and a recombination device adapted to recombine the amplified signals at the selected harmonic frequency together with the transmitted optical signals at the fundamental frequency such that the optical signals at the selected harmonic frequency are at least partially reconverted into the fundamental frequency. Such a device could be employed in an optical amplifier (such as a regenerative amplifier), an optical repeater, an oscillator, an optical switch, or as a substitute for a saturable absorber.

According to one convenient arrangement the optical device further includes switch means adapted to switch pulses of electromagnetic radiation selectively between two predetermined pathways. The switch means conveniently comprises a polarising beamsplitter. The switch means may be used in order to inject pulses of electromagnetic radiation into the device, for example to initiate the device when used as a laser. Alternatively the switch means may be used to extract electromagnetic radiation at unwanted frequencies. Conveniently the device further includes an acousto-optic modulator adapted to mode lock the device at the predetermined fundamental frequency.

Conveniently the device further includes a second nonlinear component adapted to transmit pulses of electromagnetic radiation at the predetermined fundamental frequency and to generate one or more harmonic frequency signals therefrom; and a second spectral filter device capable of differentially attenuating optical signals at the selected harmonic frequency to a greater extent than those at the fundamental frequency. Such an arrangement can be used to avoid the possibility that the intensity of electromagnetic radiation at the fundamental frequency

becomes so high that it starts to be reconverted to the selected harmonic frequency on subsequent passage through the nonlinear optical component. The second nonlinear component and the second spectral filter device together provide an intensity dependent loss at the selected harmonic frequency.

The invention further resides in a method of manipulating optical signals at a predetermined fundamental frequency comprising the steps of at least partially converting the optical signals into one or more harmonic frequency signals; amplifying the optical signals at a selected harmonic frequency; and recombining the amplified optical signals at the selected harmonic frequency together with the optical signals at the fundamental frequency such that the optical signals at the selected harmonic frequency are at least partially reconverted into the fundamental frequency. The method preferably includes the further step of differentially attenuating the signals at the fundamental frequency to a greater extent than those at the selected harmonic frequency, prior to their recombination.

The invention will now be further described, by way of example only, with reference to the accompanying drawings, in which;

Figure 1 is a schematic diagram of a nonlinear optical device in accordance with the invention;

Figures 2a to 2f are graphical representations showing the performance of the device of Figure 1 under various conditions;

Figure 3 is a schematic diagram of the device of Figure 1 when employed in a regenerative amplifier;

Figure 4 is a schematic diagram of the device of Figure 1 when employed in an alternative embodiment of regenerative amplifier; and

Figure 5 is a schematic diagram of a nonlinear optical device in accordance with an alternative embodiment of the present invention.

Referring to Figure 1 there is shown a nonlinear optical device comprising a laser 1 emitting high intensity optical pulses of fundamental frequency w, and a nonlinear crystal 2 such as Beta Barium Borate, at which the pulses are directed. The nonlinear crystal 2 partially converts the pulses of frequency w into a second harmonic signal of frequency 2 w and this signal, together with the unconverted signals at frequency w, is passed to an optical amplifier 3. The amplifier 3 is tuned to amplify optical signals at the frequency 2 w, but not those at other frequencies such as the fundamental frequency.

The optical signals emerging from the amplifier 3 are incident on a dichroic mirror 4 which has a reflectivity approaching 1 for optical signals at the second harmonic frequency 2, but a reflectivity much less than 1 for optical signals at the fundamental frequency w. Reflected signals from the dichroic mirror 4 then pass through the nonlinear crysal 2 a second time, the phase difference between the signals at w and 2 w at this stage being such that the amplified second harmonic signals are at least partially reconverted back to the fundamental. This appropriate phase relationship can be achieved either by adjusting the critical distance x in air between the crystal 2 and the mirror 4, or by employing a phase adjusting plate (not shown).

The effect of the optical device will now be described. The conversion by the nonlinear crystal 2 of optical signals from the fundamental frequency to the second harmonic frequency is intensity dependent. There then follows amplification at 2 w by the amplifier 3 and attenuation at w by the dichroic mirror 4. Thus the intensity of the reconverted signal frequency w will be critically dependent on the intensity of the initial pulse incident on the crystal 2. Figure 2a shows the effect of the device as the intensity of the incident optical signals varies, with the gain of the amplifier at 2 w set at 10 and for different reflectivities of the dichroic mirror at w ranging from 0.5 - 0.02. As can be seen from the graph, for low values of Rw, pulses of intensity of around 10^{13} W/m^2 are amplified whilst those of either higher or lower intensities are attenuated. The effect is even more dramatic with the gain of the second harmonic amplifier set at 100, although the critical intensity changes slightly. This is illustrated in Figure 2b.

With the response of the device being so dependent on the intensity of the incident pulses, the device can be used to eliminate spurious signals such as pre-pulses, pedestals or other noise which lie outside or towards the edges of the intensity window of the device. Figure 2c shows how the contrast ratio, i.e. the ratio of the peak intensity of a main pulse to that of a pre-pulse, is enhanced for an initial contrast ratio of 10:1 (i.e. the unwanted secondary pulse is 1/10th the intensity of the main pulse). The gain of the second harmonic amplifier is 10 and, as before, the different curves correspond to different values for the reflectivity of the dichroic mirror at the fundamental freqency. In Figure 2d the second harmonic amplifier gain is as before, but the initial contrast ratio is 100:1 (i.e. the unwanted pulse is 100th the intensity of the main pulse). Figures 2e and 2f show the enhancement to the contrast ratio with the gain of the second harmonic amplifier set at 100, again for initial contrast ratios of 10:1 and 100:1 respectively.

It will be seen from these figures that for an initial contrast ratio of 100:1, an amplifier gain of 100 at the second harmonic frequency, and a reflectivity of the dichroic mirror at the fundamental frequency of 0.02, the contrast ratio can be enhanced by a factor of over 1500.

Figure 3 shows the device used as part of a regenerative amplifier. In addition to the nonlinear crystal 2, amplifier 3 and dichroic mirror 4, a second dichroic mirror 5 is present, together with a switching unit 6 which is used to switch in and out pulses from a laser source 7. The additional mirror 5, in contrast to the mirror 4, has a reflectivity which approaches 100% for optical signals at the fundamental frequency w but which is considerably less for optical signals at the second harmonic frequency 2 w. Light pulses from the laser 7, which may be a simple low quality laser, are amplified, compressed, and improved in quality by repeated passes through the nonlinear device.

Figure 4 shows the regenerative amplifier of Figure 3 together with certain additional features. The switch unit comprises a polarising beamsplitter 9 and, in contrast to mirror 5 of the embodiment of Figure 3, mirror 10 has a reflectivity which approaches 100% for optical signals at the second harmonic frequency 2w but which is considerably less for optical signals at the fundamental frequency w. Between the beamsplitter 9 and the mirror 10 is an acousto-optic modulator 11.

In the alternative pathway provided by the beam splitter 9 is a further nonlinear crystal 12 and a further dichroic mirror 13, the mirror 13 having a reflectivity which approaches 100% for optical signals at the fundamental frequency w but which is considerably less for optical signals at the second harmonic frequency 2w. In operation the device will initially lase at the second harmonic frequency 2w between mirrors 4 and 10, in similar fashion to the device of Figure 3.

However, as the intensity of optical signals at the fundamental frequency w increases, the optical signals at frequency w passing back through the non-linear crystal 2, having been reflected by the mirror 4, begin to be reconverted into the second harmonic frequency 2w. This is compensated for by the beam splitter 9, crystal 12 and mirror 13 which rely on the fact that the optical signals at w and 2w are all orthogonally polarised. If the intensity of optical signals at the fundamental frequency w exceeds a predetermined threshold intensity, the further nonlinear crystal 12 begins to convert optical signals from w to 2w. The combination of the crystal 12 and the mirror 13, which has a poor reflectivity at 2w, provides an intensity dependent loss at the second harmonic frequency 2w, thereby preventing the deleterious effect on the optical signal of reconversion to the second harmonic frequency 2w.

Figure 5 illustrates an alternative embodiment of the invention. Pulses from the laser 1 pass through the nonlinear crystal 2 and the second harmonic frequency signals generated thereby are amplified, as before. The amplified signals at 2 w are at least partially reconverted into signals at the fundamental frequency by a second nonlinear crystal 8. Even though such an arrangement does not improve the quality of the pulses, it does offer certain advantages. Firstly, it operates as an amplifier of optical signals at the fundamental frequency, but as the actual amplification takes place at the second harmonic frequency, amplified spontaneous emmision (ASE) at the fundamental freqency is minimised. Secondly, the apparatus enables an amplifier tuned to a second harmonic frequency in the visible region of the electromagnetic spectrum to provide pulses at a fundamental frequency in the infrared region of the spectrum.

Claims

1. A nonlinear optical device comprising a source of intense pulses of electromagnetic radiation at a predetermined fundamental frequency; a nonlinear optical component adapted to transmit the pulses of electromagnetic radiation and to generate one or more harmonic frequency signals therefrom; an amplifier tuned to amplify optical signals at a selected harmonic frequency; and a recombination device adapted to recombine the amplified signals at the selected harmonic frequency together with the transmitted signals at the fundamental frequency such that the optical signals at the selected harmonic frequency are at least partially reconverted into the fundamental frequency.

2. An optical device according to claim 1 wherein there is additionally provided a spectral filter device capable of differentially attenuating optical signals at the fundamental frequency to a greater extent than those at the selected harmonic frequency.

3. An optical device according to claim 1 or claim 2 wherein the nonlinear optical component is adapted to generate a second harmonic frequency optical signal as the selected harmonic frequency.

4. An optical device according to any of claims 1 to 3 wherein the nonlinear optical component additionally constitutes the recombination device.

5. An optical device according to any of claims 1 to 4 wherein the nonlinear optical component comprises a frequency doubling crystal.

6. An optical device according to any of claims 2 to 5 wherein the spectral filter device comprises a dichroic mirror.

7. A nonlinear optical device comprising a nonlinear optical component adapted to transmit pulses of electromagnetic radiation at a predetermined fundamental frequency and to generate one or more harmonic frequency signals therefrom; a spectral filter device capable of differentially attenuating optical signals at the fundamental frequency to a greater extent than those at a selected harmonic frequency; an amplifier tuned to amplify optical signals at the selected harmonic frequency; and a recombination device adapted to recombine the amplified signals at the selected harmonic frequency together with the transmitted optical signals at the fundamental frequency such that the optical signals at the selected harmonic frequency are at least partially reconverted into the fundamental frequency.

8. An optical device according to claim 7 and further including switch means adapted to switch pulses of electromagnetic radiation selectively between two predetermined pathways.

9. An opitcal device according to claim 8 wherein the switch means comprises a polarising beamsplitter.

10. An optical device according to any of claims 7 to 9 and further including an acousto-optic modulator adapted to mode lock the device at the predetermined fundamental frequency.

11. An optical device according to any of claims 8 to 10 and further including a second nonlinear component adapted to transmit pulses of electromagnetic radiation at the predetermined fundamental frequency and to generate one or more harmonic frequency signals therefrom; and a second spectral filter device capable of differentially attenuating optical signals at the selected harmonic frequency to a greater extent than those at the fundamental frequency.

12. An optical amplifier incorporating a nonlinear optical device according to any of claims 7 to 11.

13. An amplifier according to claim 12 wherein the amplifier is a regenerative amplifier.

14. An optical repeater incorporating a nonlinear optial device according to any of claims 7 to 11.

15. An oscillator incorporating a nonlinear optical device according to any of claims 7 to 11.

16. An optical switch incorporating a nonlinear optical device according to any of claims 7 to 11.

17. A method of manipulating optical signals at a predetermined fundamental frequency comprising the steps of at least partially converting the optical signals into one or more higher harmonic frequency signals; amplifying the optical signals at a selected harmonic frequency; and recombining the amplified optical signals at the selected harmonic frequency together with the optical signals at the fundamental frequency such that the optical signals at selected harmonic frequency are at least partially reconverted into the fundamental frequency.

18. A method according to claim 17 including the further step of differentially attenuating the optical signals at the fundamental frequency to a greater extent than those at the selected harmonic frequency, prior to their recombination.

Fig. 1.

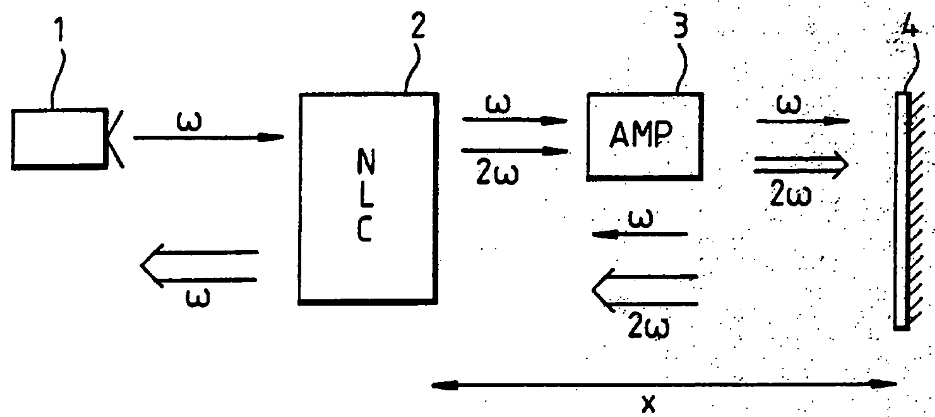
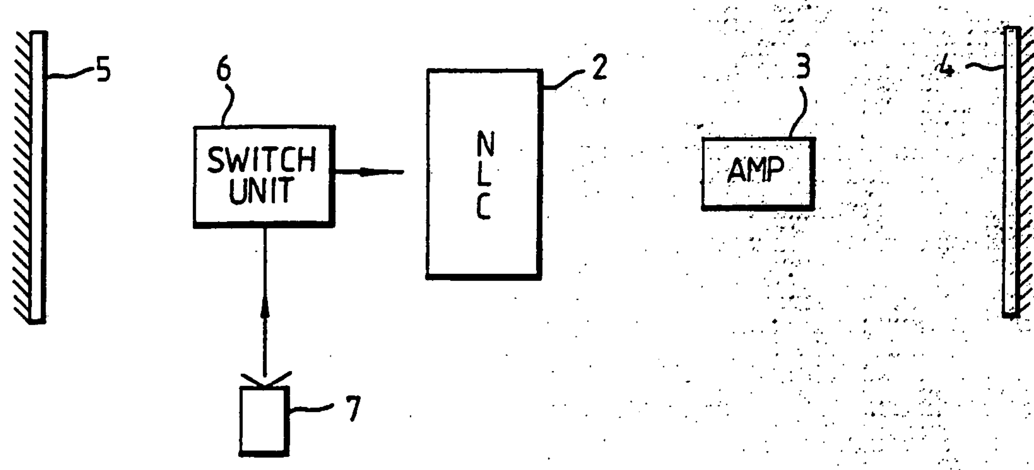
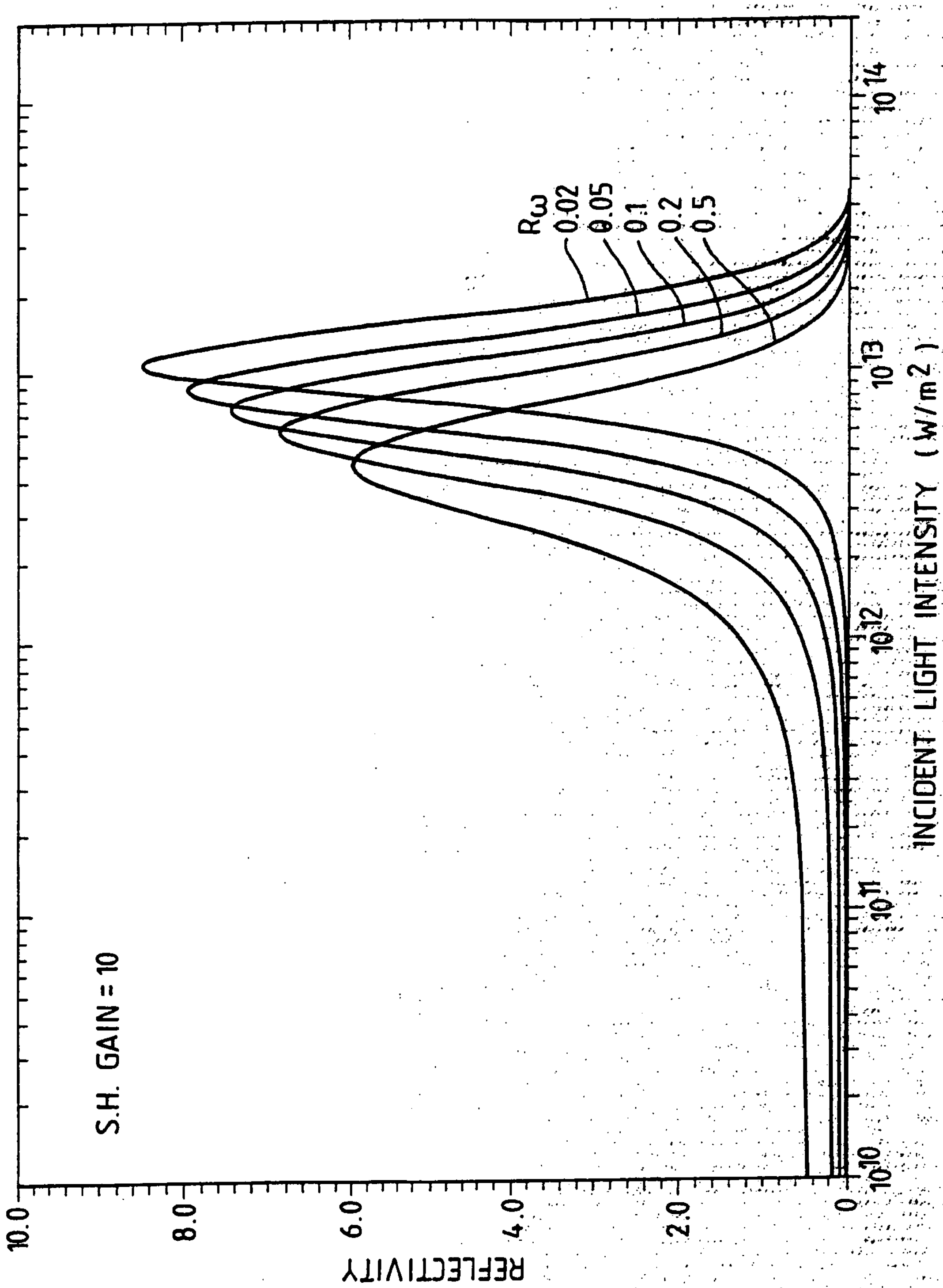


Fig. 3.

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0.1
0.2
0.5
REFLECTIVITY
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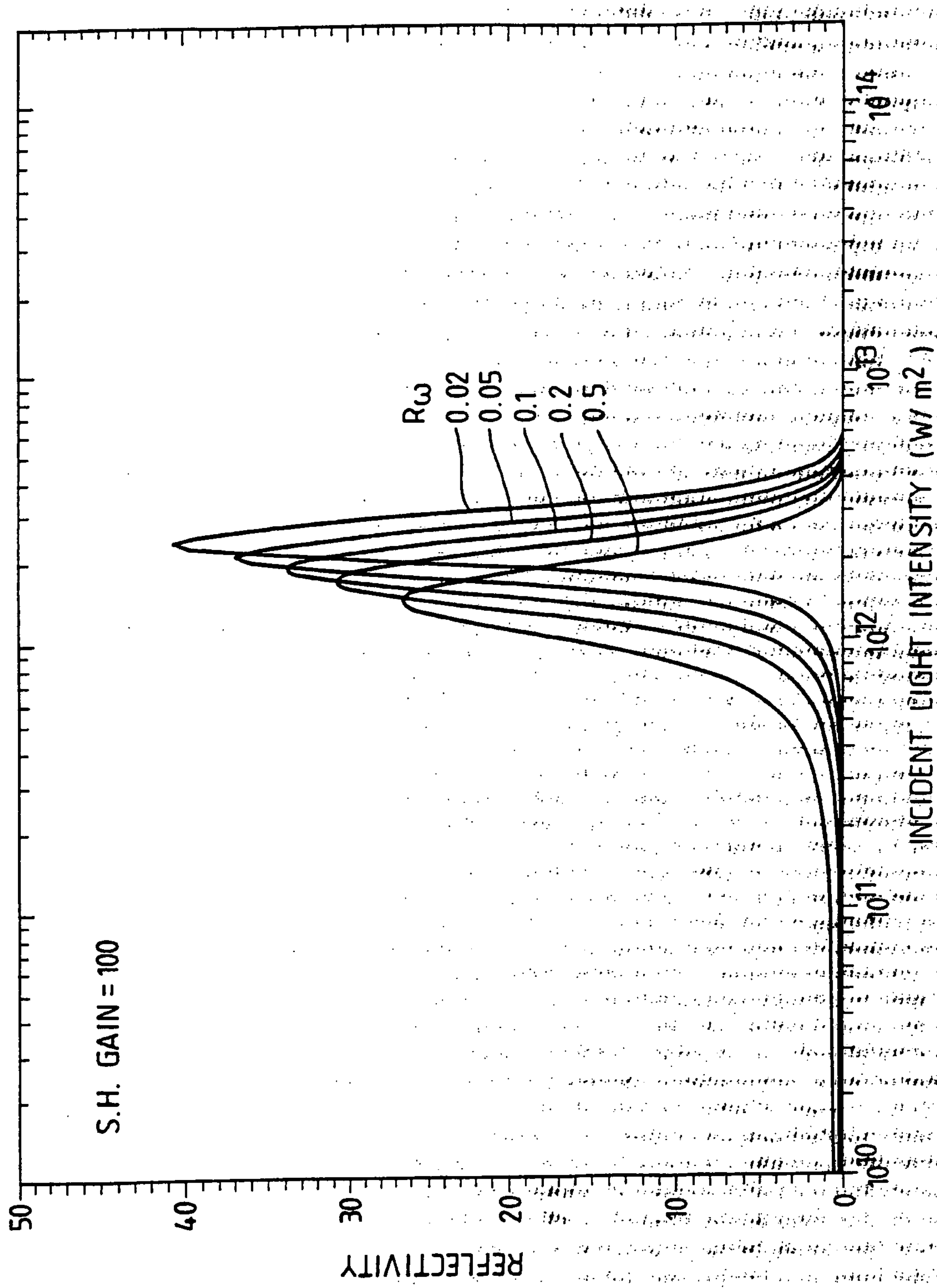
4.0
2.0
0
INCIDENT LIGHT INTENSITY (W/m^2)
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}

Fig. 2(a)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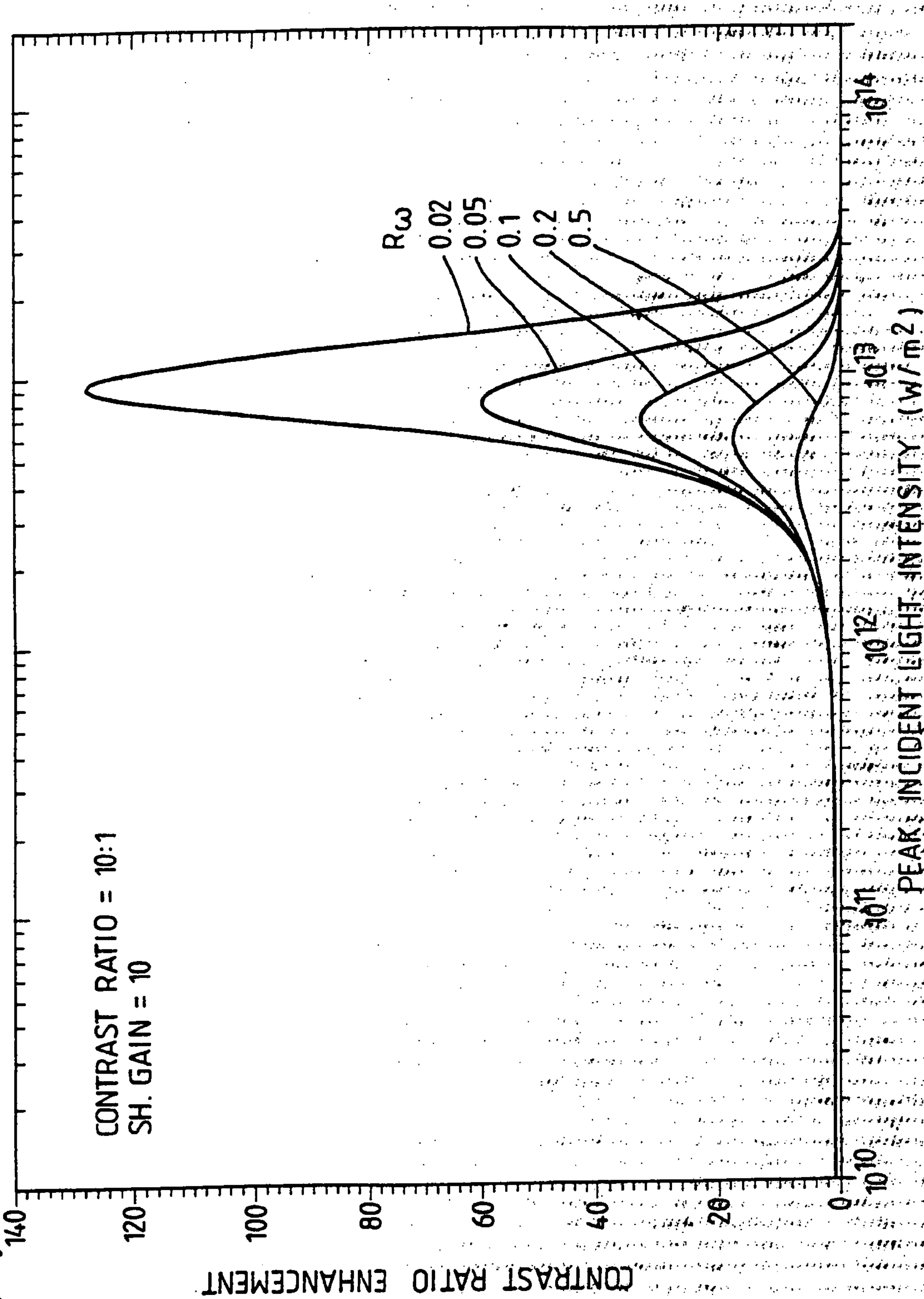
INCIDENT LIGHT INTENSITY (W/ m^2)

Fig. 2(b)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0.1
0.2
0.5
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100
80
60
40
20
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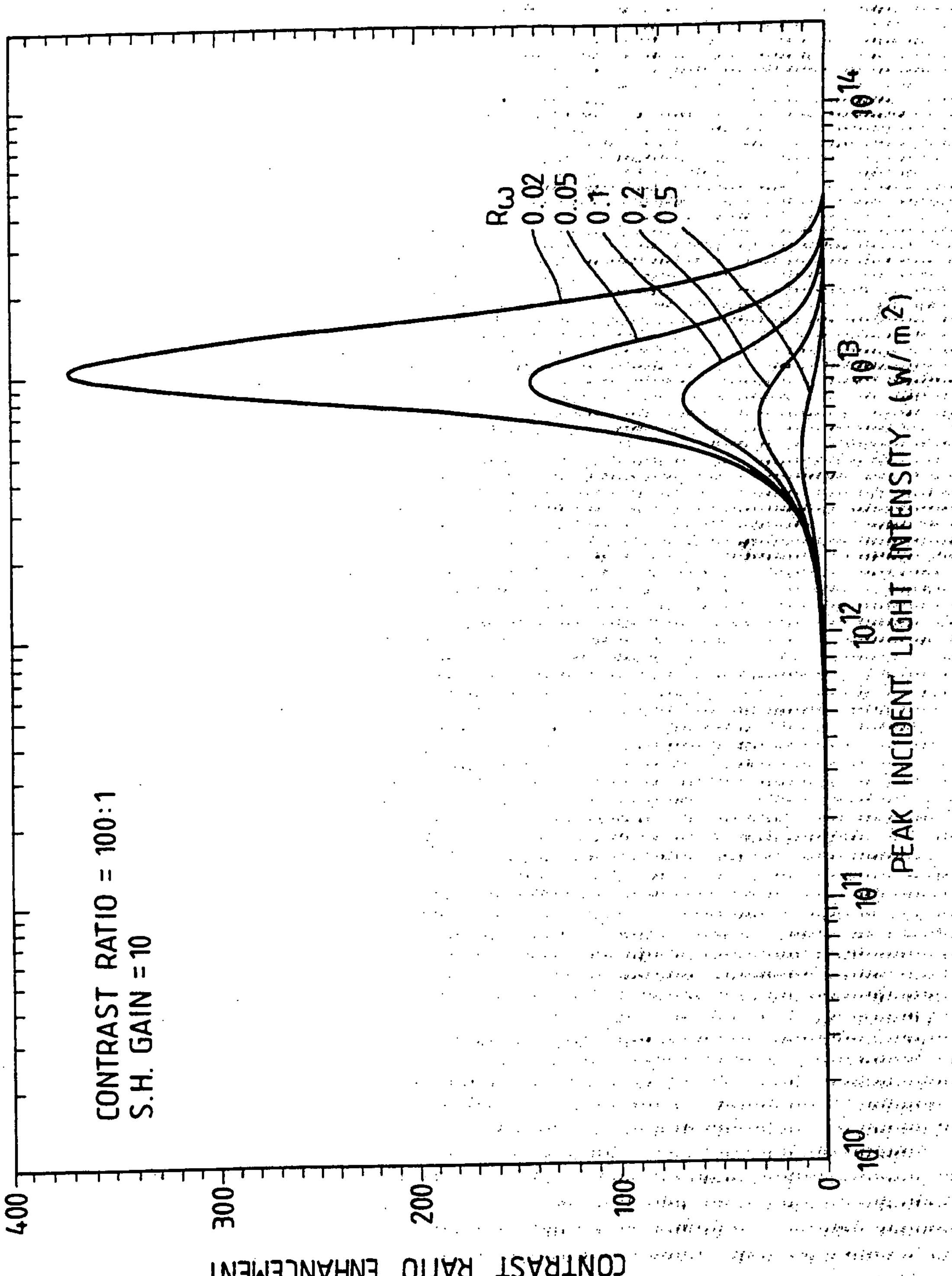
10^{12}
10^{13}
10^{14}

Fig. 2(c)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200
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400
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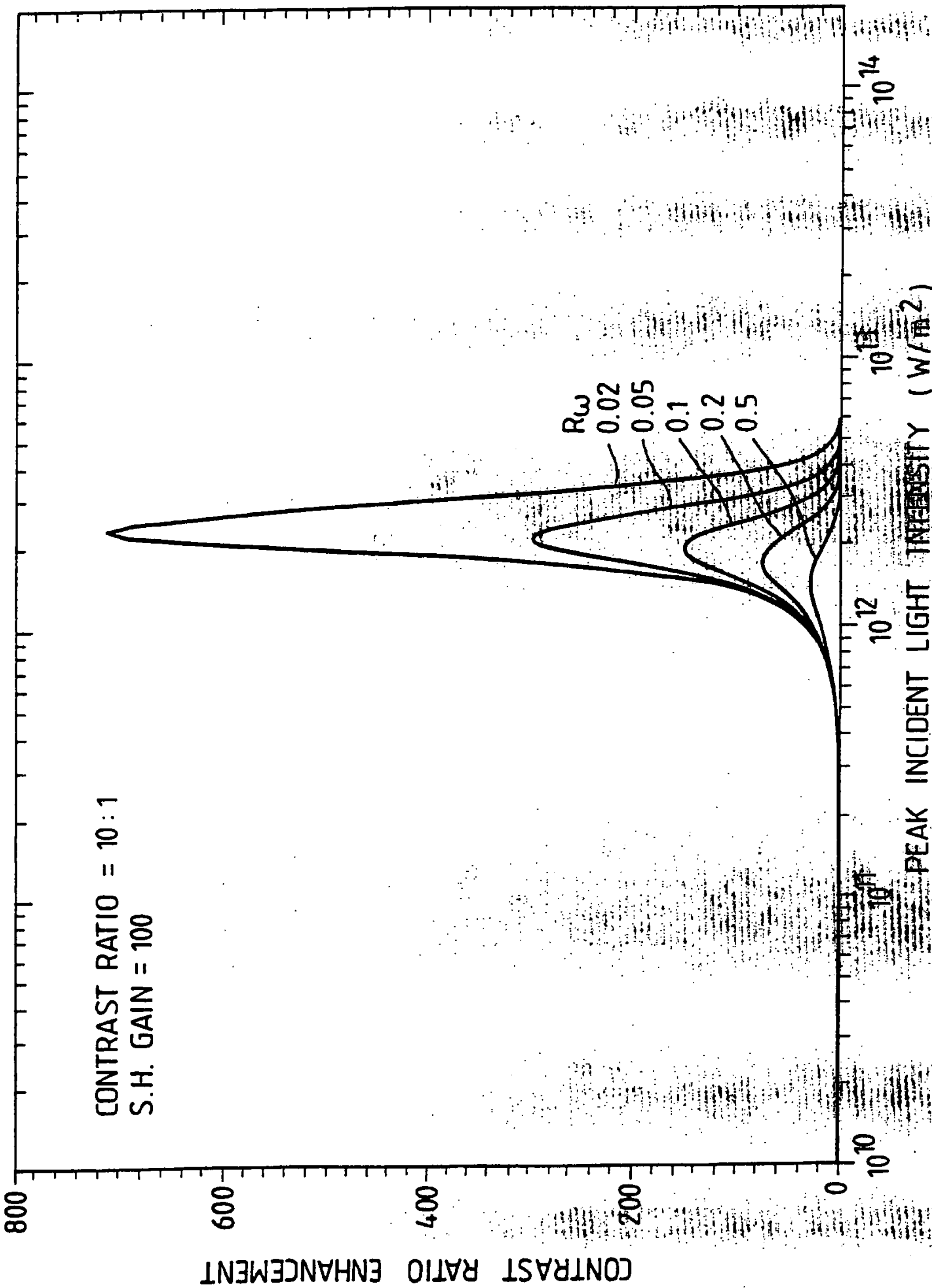
10^{12}
10^{13}
10^{14}

Fig. 2(d)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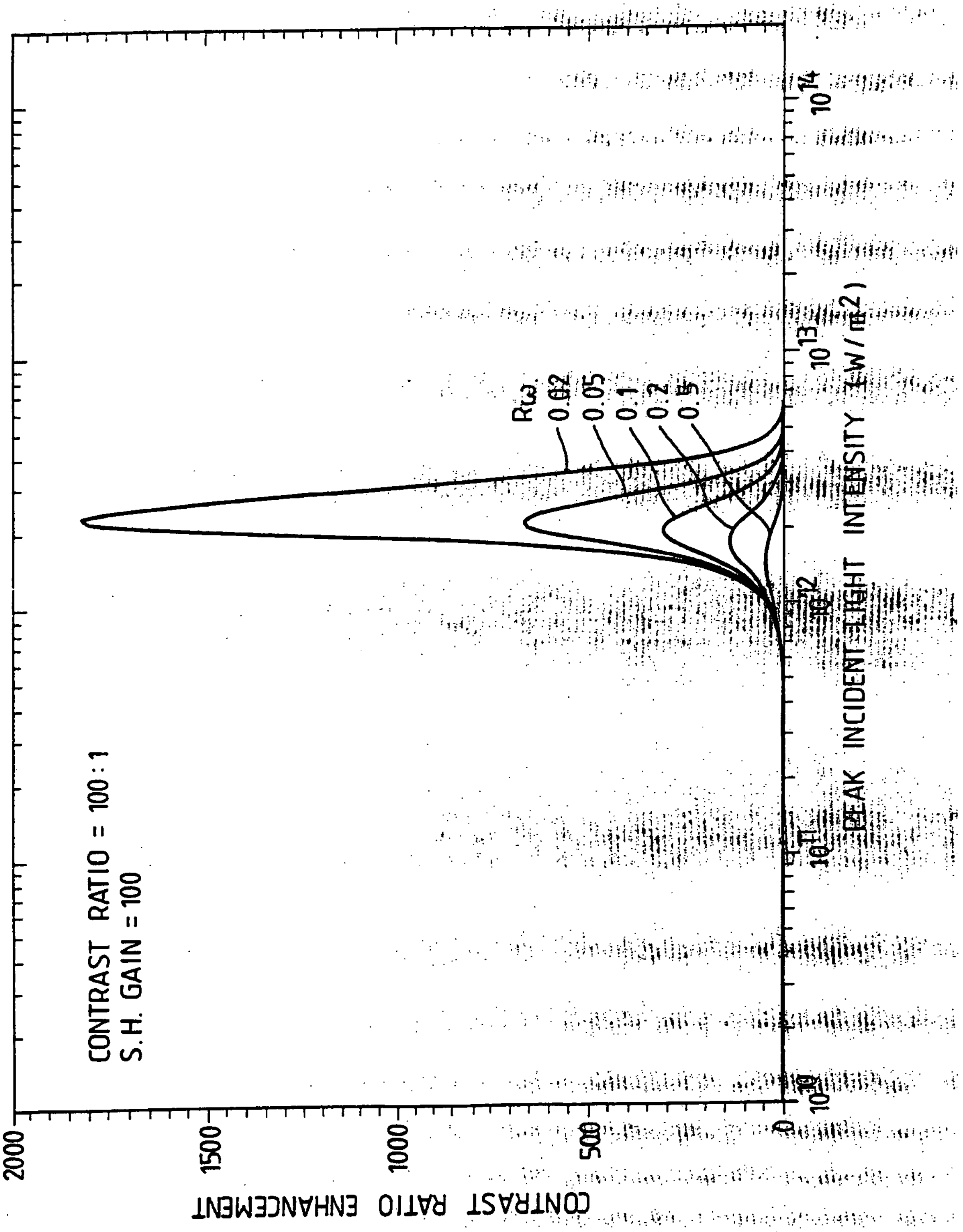
PEAK INCIDENT LIGHT INTENSITY (W/m^2)

Fig. 2(e)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10^{12}
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10^{14}
PEAK INCIDENT LIGHT INTENSITY (W/m2)

Fig. 2(f)

Fig. 4.

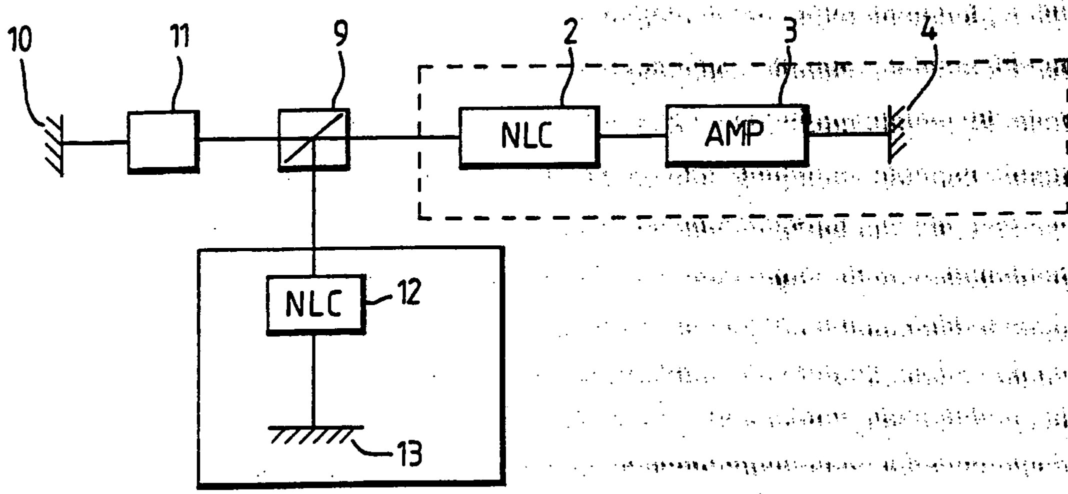
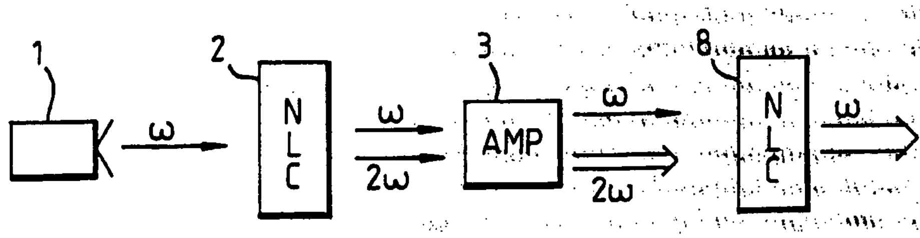


Fig. 5.



INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 90/01387

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC^5: H 01 S 3/108, H 01 S 3/23, H 01 S 3/098

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
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Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category [*]	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
A	EP, A, 0314171 (MAX-PLANCK GESELLSCHAFT ZUR FÖRDERUNG DER WISSENSCHAFTEN E.V.) 3 May 1989 see column 4, lines 8-37	1-18

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IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
12th December 1990	22.01.91
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EUROPEAN PATENT OFFICE	Natalie Weinberg

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP-A- 0314171	03-05-89	DE-A- 3736881	18-05-89
		DE-A- 3826716	08-02-90
		JP-A- 1147881	09-06-89
		US-A- 4914658	03-04-90

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